SCRREEN2

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FACTSHEETS UPDATES **BASED ON THE EU FACTSHEETS 2020**

SILVER

AUTHOR(S):

SCRREEN
Solutions for CRitical Raw materials - a European Expert Network

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Horizon 2020 Programme

SILVER

OVERVIEW

Silver (chemical symbol Ag) is a chemical element with atomic number 47. Silver is one of the eight precious, or noble metals which are resistant to corrosion. This metal is soft, very malleable and ductile and has the highest electrical and thermal conductivity of all metals (Lenntech, 2016). The presence of silver in the earth's crust is somewhat rare, with 53 parts per million upper crustal abundance (Rudnick & Gao, 2003). Silver is almost always monovalent in its compounds, but an oxide, a fluoride, and a sulphide of divalent silver are known. It is not a chemically active metal, but reacts with nitric acid (forming the nitrate) and by hot concentrated sulphuric acid. It does not oxidize in air but reacts with the hydrogen sulphide present in the air, forming silver sulphide (tarnish). This is why silver objects need regular cleaning. Silver is stable in water.

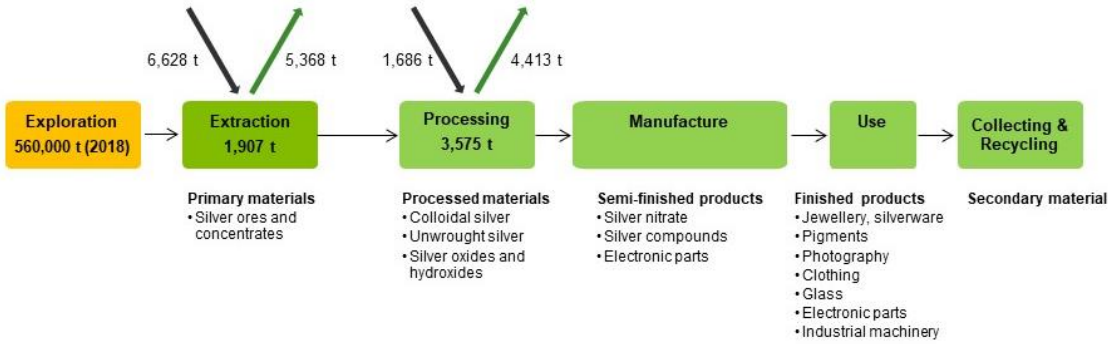

Figure 1. Simplified value chain for silver in the EU[1]

Table 1. Silver supply and demand in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
27,476	Mexico 24% Peru 14% China 13% Chile 5% Russia 5%	19,514	71%	Mexico 41% Argentina 27% Peru 15% Bolivia 11% Canada 2%	54%

Prices: Silver prices increased significantly in 2011 and reached a historical maximum of US$ 35/troy ounce (USGS, 2022). Central banks aimed to reduce the price of precious metals after 2011, which led to a normalization of the price level of silver compared with the pre-2010 level (EC, 2020). This normalisation is even more obvious after 2013, where prices ranged from US$ 16/troy ounces in 2018 to US$ 23/troy ounce in 2013. Silver prices are more volatile than gold because silver markets are smaller than other metals (e.g., gold), a lower market liquidity, and demand fluctuations between industrial uses and investments (EC, 2020).

[1] JRC elaboration on multiple sources (see next sections)

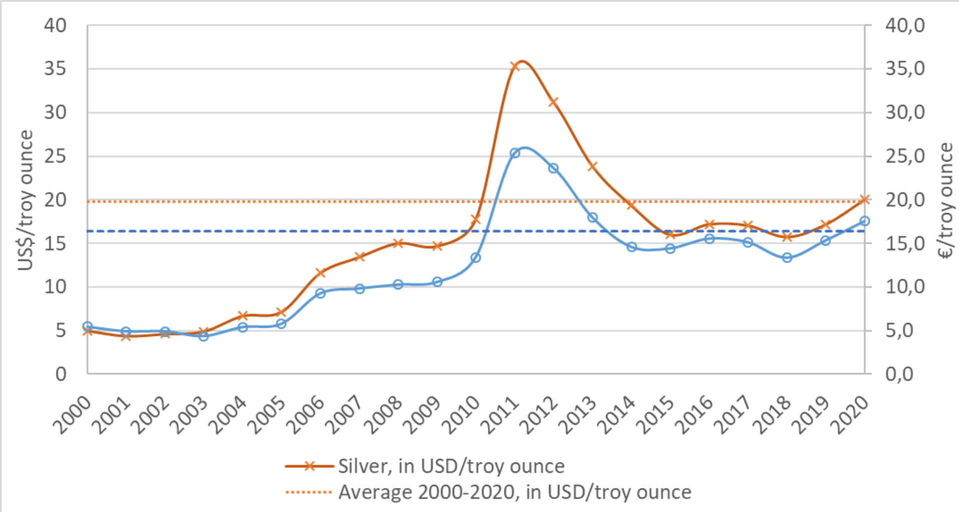

Figure 2. Annual average price of silver between 2000 and 2020 (USGS, 2021)[2].

Primary supply: According to the Silver Institute, in 2021 the global supply of silver, including primary and secondary sources, reached 31,017 t, which is a 5% increase over 2020, whereas the demand was slightly higher with 32,622 t (a 19% increase over 2020) (Metal Focus Team 2022). In 2020, domestic silver mining within the EU produced 1,961 t Ag (Eurostat, 2022). This amount mostly feed into European supply chains, reducing the import reliance. Mexico is the world's largest silver ore producer, contributing about 24% of the total world supply. This counry is by far the largest producer of silver ore, while most other countries produce silver as a by-product from mines targeting other metals. In 2021, 72% of mined silver production came from lead-zinc, copper, and gold mines.

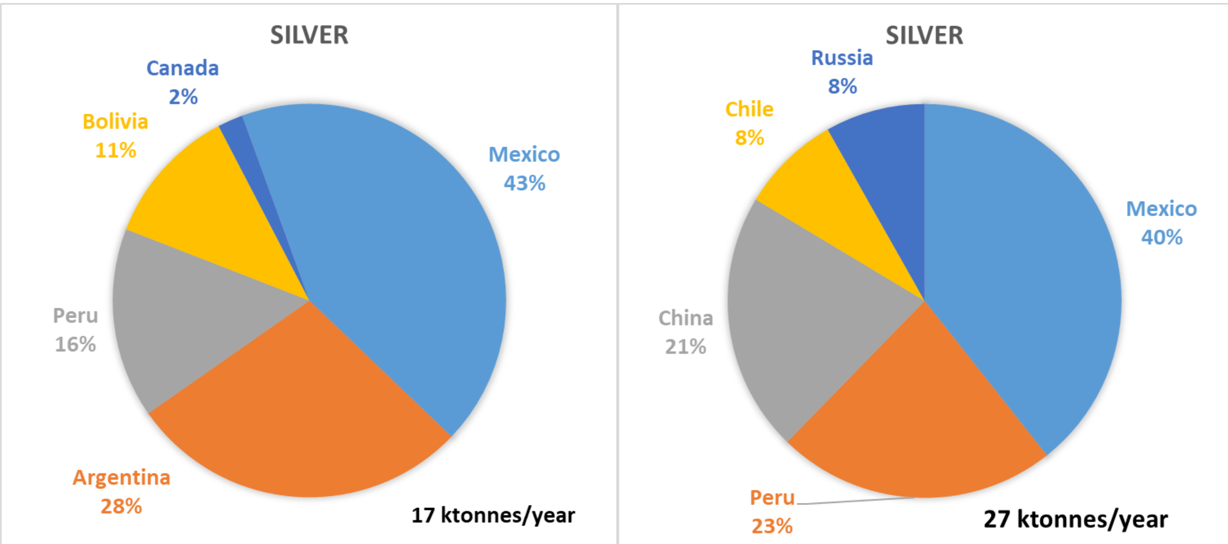

Figure 3. EU sourcing of silver and global mine production (average 2016-2020)

Secondary supply: The end-of-life recycling input rate for silver globally is estimated to be 19% in 2020. It must be said that several other percentages of the End-of-life recycling input rate (EoL-RIR) are reported, ranging

[2] Values in €/kg are converted from original data in US$/kg by using the annual average Euro foreign exchange reference rates from the European Central Bank (https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html)

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between 20% (GFMS, 2015; 2019) and 80% (UNEP, 2011) (SCRREEN workshops 2019). At European level, the EoL-RIR is 4,23%, being the highest rate registered due to the high silver price. For applications where silver use is less dissipative, such as in electric and electronic parts in vehicles and electronics, losses occur in collection, shredding and metallurgical recovery operations.

Uses: Silver is used for a variety of industrial and aesthetic applications such as electronics and jewellery as well as for investment.

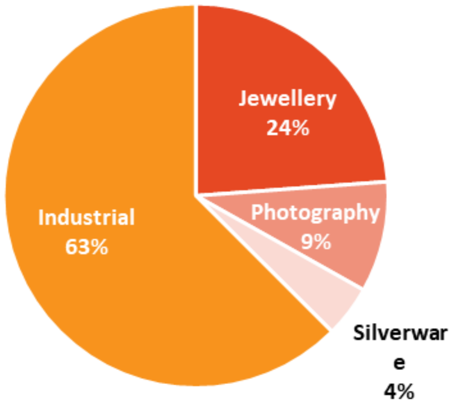

Figure 4: EU uses of silver in 2021

Substitution: In principle, silver used in jewellery (and coins and silverware) is substitutable by other metals, depending upon price and quality requirements. Copper, aluminium and other precious metals can replace silver (either completely, or partially) in many electrical and electronic uses. In brazing, substitution of silver with other metals such as tin is possible, although the physical and chemical performance in these applications of tin is reduced. Several substitution options exist to replace silver in traditional photographic applications. For example, film with reduced silver content, silver-frees black-and-white film, and xerography.

Table 2. Uses and possible substitutes

Application	%*	Substitute(s)	SubShare	Cost	Performance
Jewellery	24%	Gold	25%	Slightly higher costs (up to 2 times)	Similar
		Platinum	25%	Slightly higher costs (up to 2 times)	Similar
Photovoltaics	12%	Copper	25%	Similar or lower costs	Reduced
Batteries	7%	Nickel	35%	Similar or lower costs	Reduced
		Copper	25%	Similar or lower costs	Reduced

Other issues: Silver is a non-combustible substance, poorly flammable and practically insoluble in water. The substance is hazardous to the aquatic environment. According to (GESTIS 2022), the limit value (eight hours) of silver in air is 0.1 mg/m^3 in the European Union[3], which is higher than in the US where the limit value is 0.01 (GESTIS 2022). In general, silver is one of the most toxic metals to aquatic life in laboratory experiments. Silver nitrate and silver iodide are particularly toxic, whereas silver chloride is 300 times less acutely toxic (Australian Government, 2000).

[3] Indicative Occupation Exposure Limit Value (IOELV)

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MARKET ANALYSIS, TRADE AND PRICES

GLOBAL MARKET

Table 3: Silver (extraction) supply and demand in metric tons, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
27,476	Mexico 24% Peru 14% China 13% Chile 5% Russia 5%	19,514	71%	Mexico 41% Argentina 27% Peru 15% Bolivia 11% Canada 2%	54%

The world production of silver takes place in several countries all over the world. What should be mentioned, however, is that only around 30% of the annual supply comes from primary silver mines while more than a third is produced at lead/zinc operations and a further 20% from copper mines (Mining Intelligence, 2019). The polymetallic ore deposits from which silver are recovered account for more than two-thirds of the world's silver resources. Mexico is the world's largest silver ore producer, contributing about 24% of the total world supply, while Peru (14%) and China (13%) follow in production, before Chile and Russia standing at 5%.

The global silver ore production was 27,416 t per year, as an average over 2016-2020. Only around 30% of the annual supply comes from primary silver mines while more than a third is produced at lead/zinc operations and a further 20% from copper mines (Mining Intelligence, 2019). Only six of the top 20 producers are primary silver miners. The polymetallic ore deposits from which silver are recovered account for more than two-thirds of the world's silver resources.

The main players in silver production are Industrias Penoles (Mexico), Fresnillo (Mexico), Polymetal International (Russia), Pan American Silver Corp (Canada), Wheaton Precious Metals (Canada), Coeur Mining (North & South America), and Buenaventura Mining (Peru).

Reserves are estimated around 530,000 tons worldwide, and are important in Peru (120,000 tons), Australia (90,000 tons), and Poland (67,000 tons.) Silver ore production increased from 2020 to 2021 in Argentina, India, Mexico, and Peru following shutdowns due to the covid-19 pandemic (USGS, 2022a).

Besides its monetary uses and investment perspectives that are not taken into consideration in this criticality assessment, silver is mostly used in the production of jewellery (21-25%) and silverware (5-8%), photography (4-5%), photovoltaics (11-13%), electronic parts (6-7%), while it is widely used in the automotive industry (8-9%), in catalysts (7-8%), batteries (7-8%), brazing & soldering (7-8%), glass (6-7%) and other parts, bearings (6-7%), as well as in medicine (4%).

Though the use of silver in investments and monetary applications is not taken into consideration in this critical assessment, it should be noted that the silver market is quite big, which makes it one of the largest and most important financial markets in the modern economy. Given its size and liquidity, silver is clearly an asset for jewelleries and silverware.

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Silver demand should be boosted in the future, due to the expectation for exponential growth of electric vehicles (EVs) and continued investment in solar photovoltaic energy. However, silver might be Furthermore, the use of inductively coupled power transfer technology to wirelessly charge vehicles using silver-plated induction coils, as well as the use of silver in the generation of nuclear energy may significantly contribute to the low-carbon economy that EU is pursuing for 2050.

EU TRADE

Silver is assessed at Mining and processing/refining stage. The following table lists relevant Eurostat CN trade codes for silicon metal.

Table 4 Relevant Eurostat CN trade codes for Silver

Mining		Processing/refining	
CN trade code	**title**	**CN trade code**	**title**
261610	Silver Ores and Concentrates	**284321**	Silver Nitrate
		7106	Silver including silver plated with gold or platinum or semimanufactures

Figure 5 shows the import and export trend of Silver Ores and Concentrates. The EU exports and imports used to be at the same level between 2001-2005. The increase in import of Silver Ores and Concentrates was started from 2006 and reached to 33,665 tonnes in 2021. The export of Silver Ores and Concentrates showed to be relatively stable during 2000-2010. From 2010, the export began to increase until 2017 and then reached to zero in 2018 and raised again to turn to 13,984 tonnes in 2021.

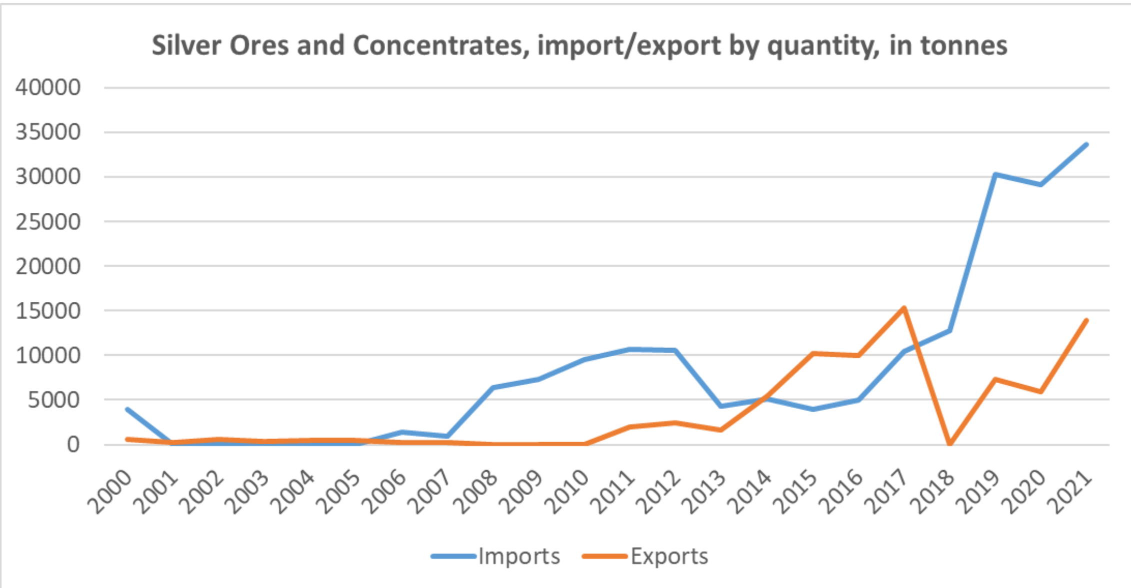

Figure 5. EU trade flows of Silver Ores and Concentrates (CN 261610) from 2000 to 2021 (Eurostat, 2022)

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Figure 6 illustrates the share of import in EU for Silver Ores and Concentrates from various countries. The main import partners of EU are Mexico (30%), Peru (28%), Argentina (24%), Bolivia (8%). The import of Silver Ores and Concentrates from Mexico started from 2012 with 1,036 tonnes and reached to 9, 174 tonnes in 2021. The import of Silver Ores and Concentrates from Morocco was increased during 2020 and 2021.

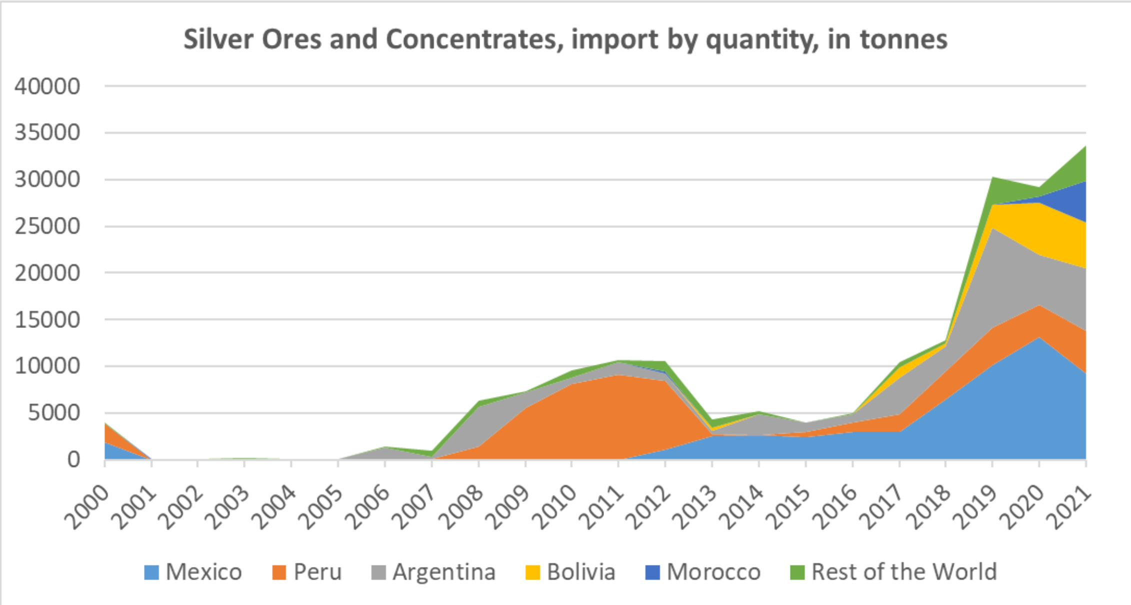

Figure 6. EU imports of Silver Ores and Concentrates (CN 261610) from 2000 to 2021 (Eurostat, 2022)

Figure 7 shows the import and export trend of Silver Nitrate. During the year 2000-2018, the EU import showed a higher quantity than export while after 2018, the EU export increased to the higher amount than import. During 2000-2007, the EU import of Silver Nitrate increased from 309 tonnes in 2000 to 623 tonnes in 2007 with some fluctuations but from 2008 the EU import had a declining trend till 2020 reaching 198 tonnes.

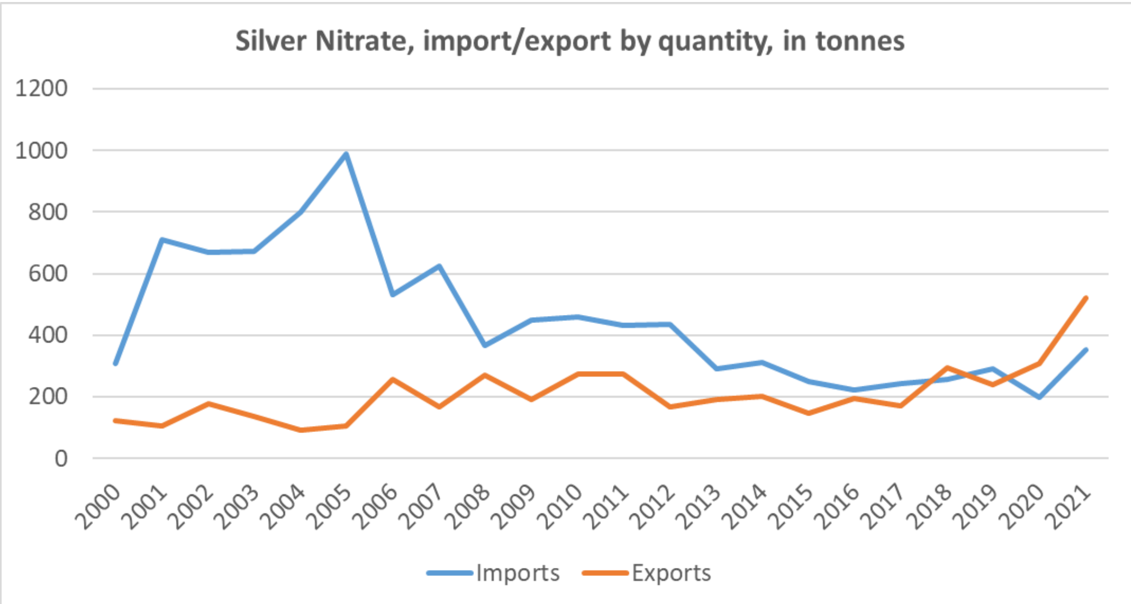

Figure 7. EU Trade flows of Silver Nitrate (CN 284321) from 2000 to 2021 (Eurostat, 2022)

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Figure 8 illustrates the share of import in EU for Silver Nitrate from various countries. The import of Silver Nitrate to EU in the past two decades (2000-2021) fluctuated rather greatly. The main import partners of EU are UK (83%), Brazil (15%) and North Macedonia (1%). UK used to be the main supplier in all time (2000-2021).

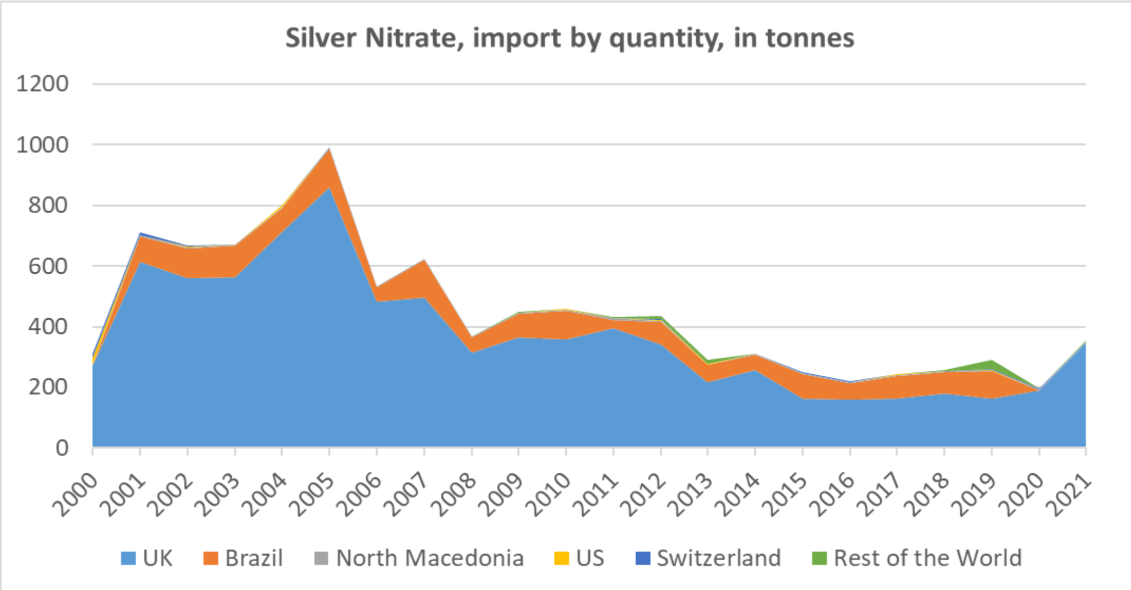

Figure 8. EU imports of Silver Nitrate (CN 284321) by country from 2000 to 2021 (Eurostat, 2022)

Figure 9 shows the import and export trend of Silver including silver plated with gold or platinum or semimanufactures. The EU import is lower than the EU import of Silver including silver plated with gold pr platinum or semimanufactures. In 2021, the EU export sat at 4,580 tonnes while the import was 3,231 tonnes. EU export started to experience a high jump from 2,372 tonnes in 2003 to 255,095 tonnes in 2004 and again decreased.

Figure 9. EU trade flow of Silver including silver plated with gold or platinum or semimanufactures (CN 7106) by country from 2000 to 2021 (Eurostat, 2022)

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Figure 10 illustrates the share of import in EU for Silver including silver plated with gold pr platinum or semimanufactures from various countries. The main supplier to EU in the past two decades (2000-2021) was Switzerland (23% of share), followed by US, UK, Kazakhstan and Japan (21%, 20%, and 7%, 6%, respectively).

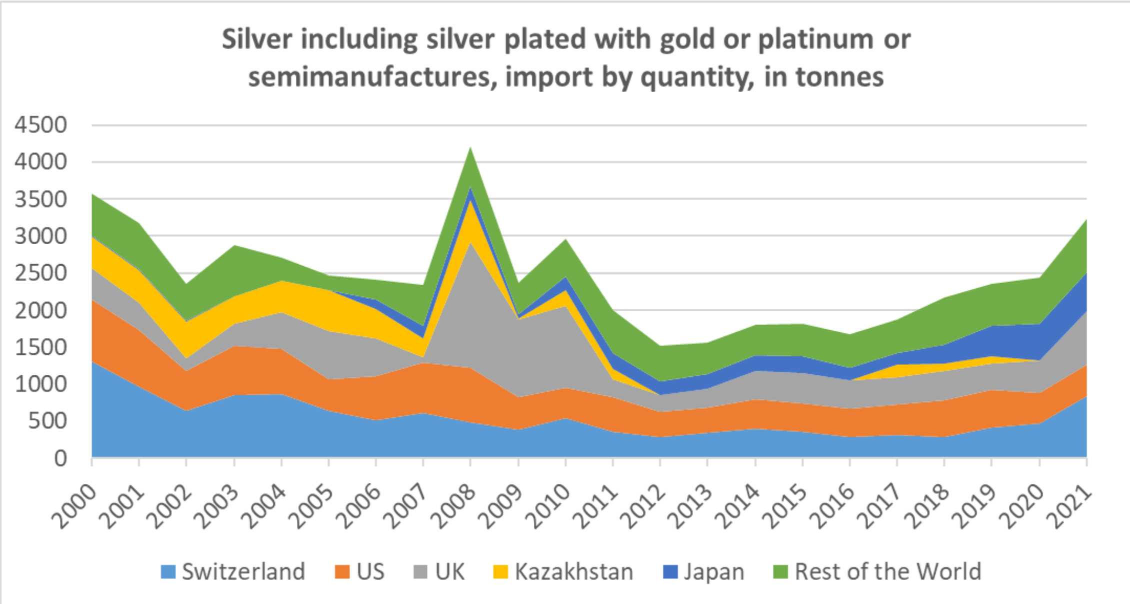

Figure 10. EU imports of Silver including silver plated with gold or platinum or semimanufactures (CN 7106) by country from 2000 to 2021 (Eurostat, 2022)

PRICE AND PRICE VOLATILITY

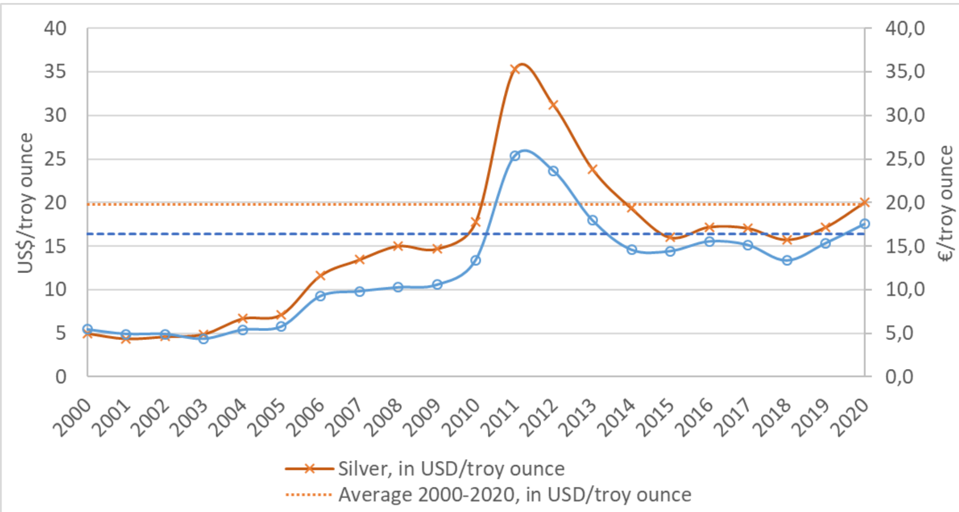

Figure 11. Annual average price of silver between 2000 and 2020, in US$/troy ounce and €/ troy ounce[4]. Dash lines indicate average price for 2000-2020 (USGS, 2022b)

[4] Values in €/kg are converted from original data in US$/kg by using the annual average Euro foreign exchange reference rates from the European Central Bank

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Silver prices increased significantly in 2011 and reached a historical maximum of US$ 35/troy ounce (USGS, 2022). Central banks aimed to reduce the price of precious metals after 2011, which led to a normalization of the price level of silver compared with the pre-2010 level (EC, 2020). This normalisation is even more obvious after 2013, where prices ranged from US$ 16/troy ounces in 2018 to US$ 23/troy ounce in 2013. Silver prices are more volatile than gold because silver markets are smaller than other metals (e.g., gold), a lower market liquidity, and demand fluctuations between industrial uses and investments (EC, 2020).

DEMAND

GLOBAL AND EU DEMAND AND CONSUMPTION

As an average for the period 2012-2016, the EU consumes about 3,167 t of silver in form of ores and concentrates (Eurostat, 2019b). As a percentage of apparent consumption, the import reliance for silver is 18%. When it comes to processed silver and silver metal, the EU consumes 849 t in the same period 2012-2016. The EU is a net exporter of Silver metal (Eurostat, 2019b).

The Silver Institute (2022) estimates the annual average worldwide consumption of silver as about 27.4 ktonnes for 2017-2021.

Silver extraction stage EU consumption is presented by HS code CN 26161000 Silver ores and concentrates. Import and export data is extracted from Eurostat Comext (2022). Production data is extracted from WMD (2022).

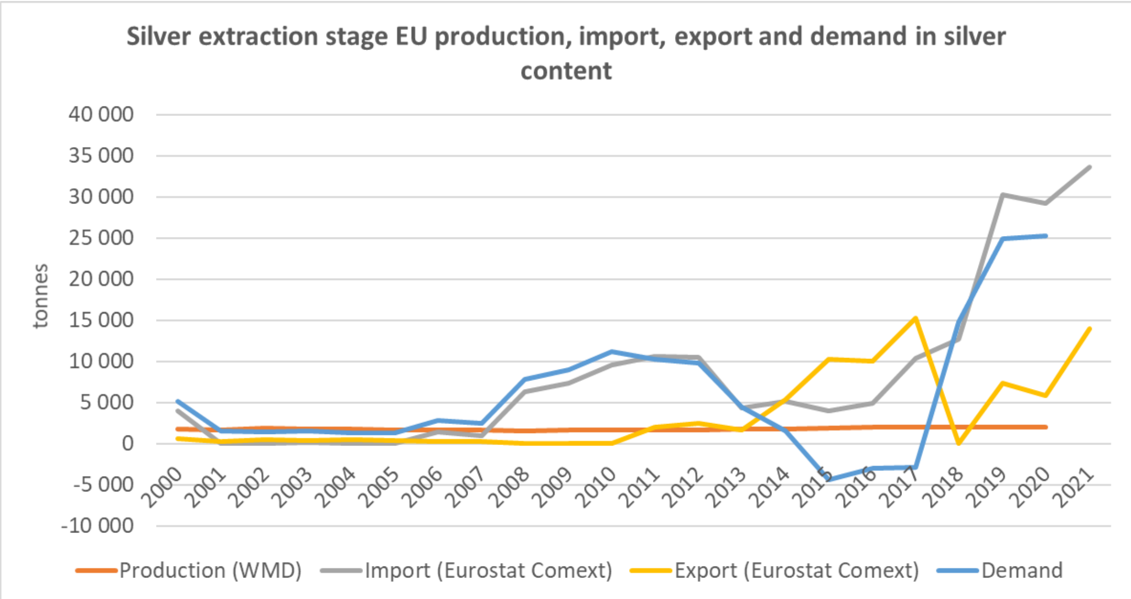

Figure 12. Silver (CN 26161000) processing stage apparent EU consumption. Production data is available from WMD (2022). Consumption is calculated in silver content (EU production+import-export).

(https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html)

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Silver extraction / processing stage EU consumption is presented by HS code CN 7106 Silver including silver plated with gold or platinum, semi-manufactured. Import and export data is extracted from Eurostat Comext (2022). Production data is extracted from Eurostat Prodcom (2022) using PRCCODE 24411050 - Silver, in semi-manufactured forms (including plated with gold or platinum) (excluding unwrought or in powder form) and PRCCODE 24411030 Silver, unwrought or in powder form (including plated with gold or platinum). For year 2004, the Eurostat Comext gives an export of 25 ktonnes which result in a demand of -12 ktonnes.

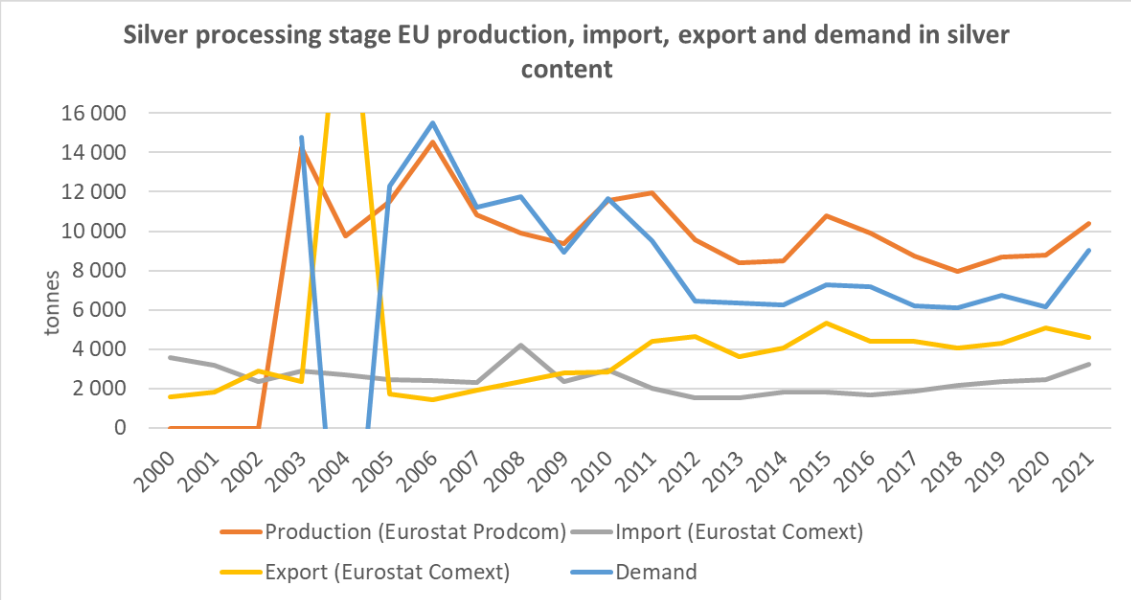

Figure 13. Silver (CN 7106) processing stage apparent EU consumption. Production data is available from Eurostat Prodcom (2022) for 2003-2021. Consumption is calculated in silver content (EU production+import-export).

Based on Eurostat Comext (2022) and Eurostat Prodcom (2022) average import reliance of silver is at extraction stage 54.1 % and at processing stage 0 % for 2016-2020.

GLOBAL AND EU USES AND END-USES

Silver is used for a variety of industrial and aesthetic applications such as electronics and jewellery as well as for investment.

About one quarter of the global silver demand in 2021 came from investment (The Silver Institute, 2022). For the criticality assessment, these monetary silver applications are not relevant, while the non-monetary and industrial applications are of interest. Accordingly, as in previous criticality assessments that have been carried out, only these latter applications will be taken into consideration.

The development of the end uses of silver is shown in Figure 14 for Europe and in Figure 15 globally.

The major applications of silver are within the industrial sector, accounting for 63 % of the European silver demand in 2021. Within these, silver is used for electronic goods, photovoltaics, as a brazing alloy or solder, and in other industrial applications. Global silver demand for photovoltaics more than doubled globally

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between 2012 and 2021. Appropriately, the European demand share for industrial applications, which is not further disaggregated into specific sectors in reporting, increased. By contrast, the global silver demand for photography decreased by 60 % within the last decade. The European demand for photography and silverware in 2021 is estimated, based on the European demand compared to the North American (for photography) and global (for silverware) demand of 2012 (share of demand between these regions assumed to remain constant over time).

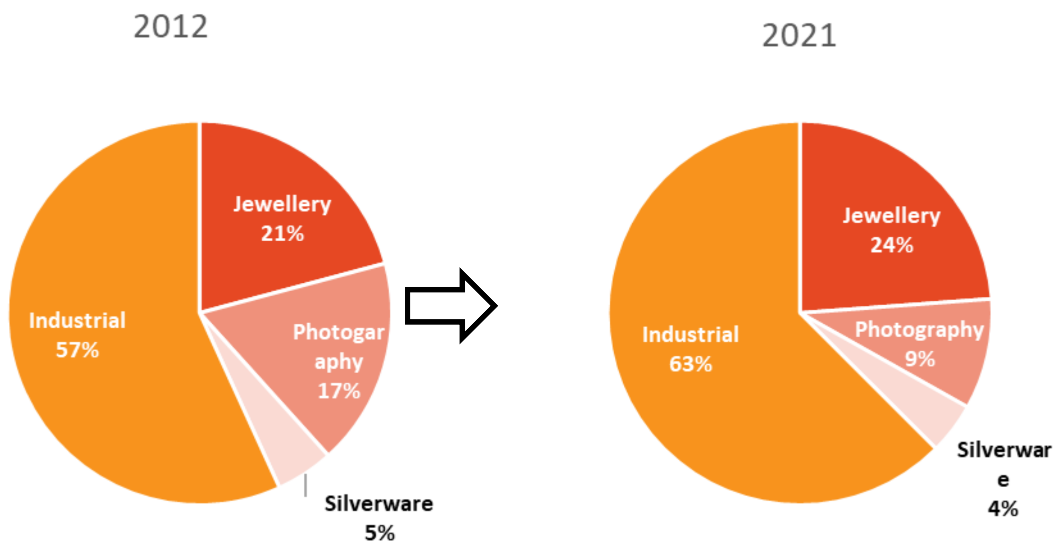

Figure 14: Estimated European end uses of silver in 2012 and 2021 (calculated based on The Silver Institute (2022))

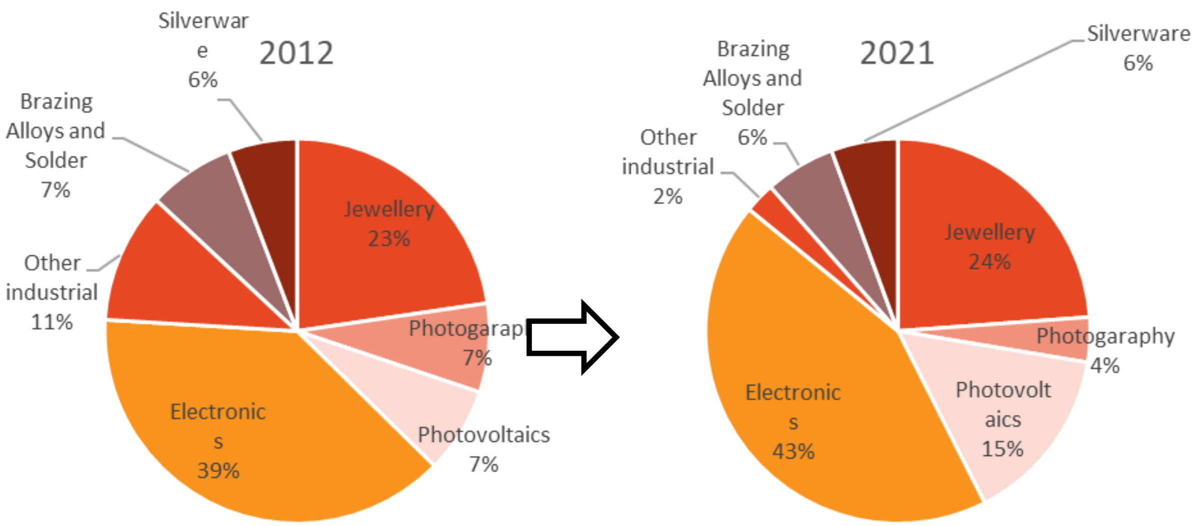

Figure 15: Global end uses of silver in 2012 and 2021 (The Silver Institute, 2022))

The relevant industry sectors and their 2- and 4-digit NACE codes are summarised in Table 5 and visualized in Figure 16

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Table 5: Silver applications, 2-digit and examples of associated 4-digit NACE sectors, and value-added per sector for 2018 (*for 2014) (Eurostat, 2021).

Applications	2-digit NACE sector	Value added of NACE 2 sector (M€)	4-digit CPA
Jewelery, Silverware, recreative products	C32- Other manufacturing	76,795* (C31-32)	32.12 - Manufacture of jewellery and related articles
Paints, oxides, photograph	C20 - Manufacture of chemicals and chemical products	117,093*	20.59 - Manufacture of other chemical products n.e.c. 20.13 - Manufacture of other inorganic basic chemicals
Automotive	C29 - Manufacture of motor vehicles, trailers and semi-trailers	234,941	29.31 - Manufacture of electrical and electronic equipment for motor vehicles
Batteries	C27 - Manufacture of electrical equipment	98,417	27.20 - Manufacture of batteries and accumulators
Industrial machinery	C28 - Manufacture of machinery and equipment n.e.c	200,030*	28.12 - Manufacture of fluid power equipment
Other transport equipment	C30 - Manufacture of other transport equipment	49,098*	30.30 - Manufacture of air and spacecraft and related machinery
Electronic parts	C26 - Manufacture of computer, electronic and optical products	84,021*	26.11 - Manufacture of electronic components
Glass	C23 - Manufacture of other non-metallic mineral products	69888	23.19 - Manufacture and processing of other glass, including technical glassware
Parts like bearings	C25 - Manufacture of fabricated metal products, except machinery and equipment	183,016	28.15 - Manufacture of bearings, gears, gearing and driving elements 25.61- Treatment and coating of metals
Medicine	C21 - Manufacture of basic pharmaceutical products and pharmaceutical preparations	94,338	C21.20 - Manufacture of pharmaceutical preparations

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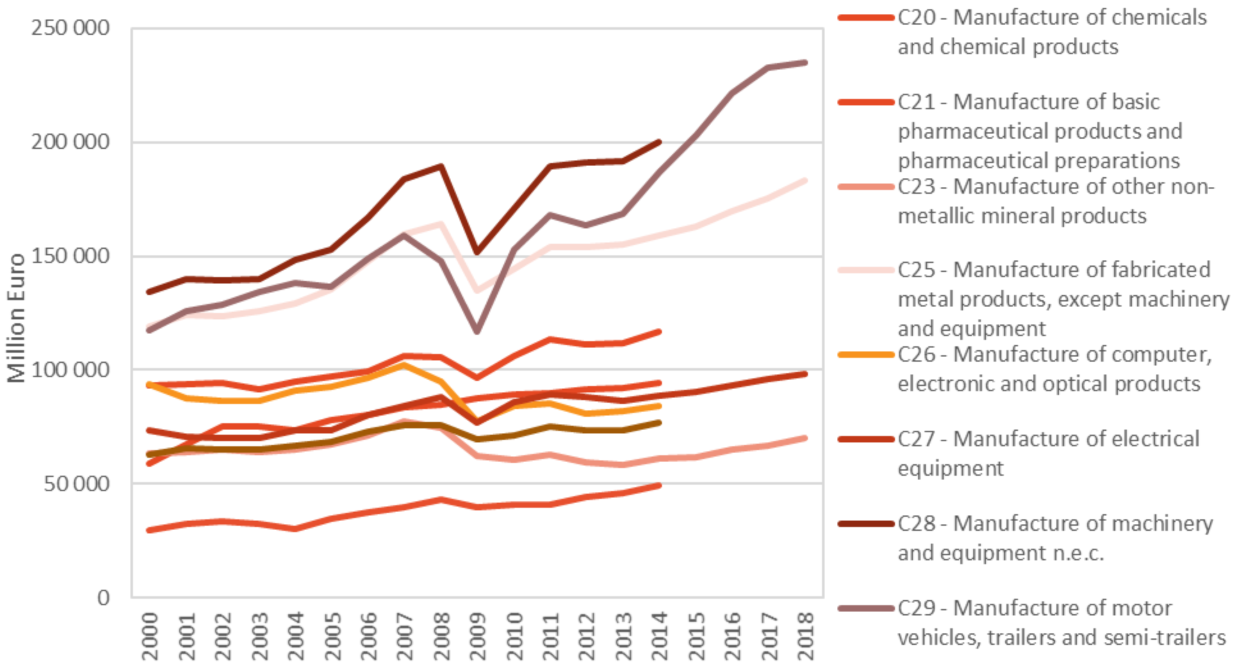

Figure 16: Value added per 2-digit NACE sector over time (Eurostat, 2021).

APPLICATIONS OF SILVER

JEWELLERY, SILVERWARE AND COINS

- Malleability, reflectivity, and luster make silver a popular precious metal for aesthetic applications. Because it is so soft, silver must be alloyed with base metals, like copper, as in the case of sterling silver (92.5% silver, 7.5% copper).
- Although it resists oxidation and corrosion, silver can tarnish, but by polishing the film can be removed.
- Because it is less expensive than gold, silver is a popular choice for jewellery and a standard for fine dining.
- Silver-plated base metals offer a less costly alternative to silver.

ELECTRICAL AND ELECTRONICS

- Silver's usage in electrical and electronics industry is widespread due to its high electrical and thermal conductivity.
- For example, it is used for electrical contacts, switches, and passive electronic components such as multi-layer ceramic capacitors. The end-markets for these components include cell phones, PCs, computers, automotive applications amongst many other uses.

PHOTOVOLTAIC

- Silver's use in PV solar cells is mainly as a conductive paste for thick film crystalline silicon cells. The use of silver in thin film solar PV or Concentrating Solar Power (CSP) is more limited.

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PAINTS

- Silver and silver-based compounds are highly antimicrobial by virtue of their antiseptic properties to several kinds of bacterium, while they also have low toxicity and are long-lasting biocides with high thermal stability and low volatility.
- Hence, a surface coated with silver-nanoparticle paint shows excellent antimicrobial properties, and for this reason silver is very popular in the painting industry (Kumar et al, 2008).

PHOTOGRAPHY

- Silver's high optical reflectivity has given its historical usage for film photography, and it had been one of the primary industrial uses of silver until the rise of digital media.
- Thus, this market has been in decline since the late 1990s.
- Traditional film photography relies on the light sensitivity of silver halide crystals present in film. When the film is exposed to light, the silver halide crystals change to record a latent image that can be developed into a photograph.

BRAZING ALLOYS AND SOLDERS

- When metal pieces such as pipes, faucets, ducts and electrical wires are joined together the process is called brazing or soldering, based on how much heat is applied to the junction. Without silver, none of these connections would be as strong, leak-proof, or as electrically conductive as the original materials.

GLASS

- Silver is almost completely reflective when polished.
- Since the 19th century, mirrors have been made by coating a transparent glass surface with a thin layer of silver, though modern mirrors also use other metals like aluminum.
- Many windows of modern buildings are coated with a transparent layer of silver that reflects sunlight, keeping the interior cool in summer months.

BEARINGS

- Engine bearings rely on silver. The strongest bearing is made from steel that has been electroplated with silver. Silver's high melting point allows it to withstand the high temperature of engines.
- Silver also acts like a lubricant to reduce friction between a ball bearing and its housing.

BATTERIES

- Another electronic application of silver is in batteries that employ silver oxide or silver zinc alloys. These lightweight, high-capacity batteries perform better at high temperature than other batteries.

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- Silver-oxide is used in button batteries that power cameras and watches, as well as in aerospace and defense applications. Silver-zinc batteries offer an alternative to other commonly applied battery-technologies.

ETHYLENE OXIDE INDUSTRY

Silver oxide is used as a catalyst in this petro-chemical industry to produce polyester intermediates.

OTHER INDUSTRIAL APPLICATIONS

Other applications include coating materials for compact disks and digital video disks as well as cellophane. Silver has also a number of emerging applications such as solid-state lighting, RFID-tags, water purification and hygiene. New markets for nano-silver are frequently being discovered.

Due to its ability to absorb oxygen, silver is being researched as a possible substitute for platinum to catalyze oxidation of matter collected in diesel engine filters.

SUBSTITUTION

Substitutes have been identified for the applications of silver.

Table 6: Substitution options for silver by application (EC Data 2022, SCRREEN2 Valid. Workshop, 2022).

Application	%*	Substitute(s)	SubShare	Cost	Performance
Jewellery	24%	Gold	25%	Slightly higher costs (up to 2 times)	Similar
		Platinum	25%	Slightly higher costs (up to 2 times)	Similar
Photovoltaics	12%	Copper	25%	Similar or lower costs	Reduced
Batteries	7%	Nickel	35%	Similar or lower costs	Reduced
		Copper	25%	Similar or lower costs	Reduced
Silverware	7%	Not assessed, below 10%			
Electronic parts	6%	Not assessed, below 10%			
Catalysts	7%	Not assessed, below 10%			
Bearings	7%	Not assessed, below 10%			
Glass	6%	Not assessed, below 10%			
Medicine	4%	Not assessed, below 10%			
Brazing and soldering	7%	Not assessed, below 10%			
Automotive Industry	8%	Not assessed, below 10%			
Photography	5%	Not assessed, below 10%			

* EU end use consumption share.

JEWELLERY AND SILVERWARE

- In principle, silver used in jewellery (and coins and silverware) is substitutable by other metals, depending upon price and quality requirements.

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- For example, gold and platinum can easily substitute for silver based on the perceived higher status of these metals.
- Stainless steel may be substituted for silver flatware

ELECTRONIC PARTS

- Silver is considered to be the optimal electrical conductor, although its higher cost and low strength properties limit its use to special applications such as joint plating and sliding contact surfaces (Silver Institute, 2019).
- Copper, aluminium and other precious metals can replace silver (either completely, or partially) in many electrical and electronic uses. Copper (which is less rare than silver) can be a more sensible option to use in several scenarios, even though silver wire is Ca.7% more conductive than copper wire of the same length.
- Nonetheless, silver wire is typically reserved for more sensitive systems and specialty electronics where high conductivity over a small distance is essential.

BRAZING AND SOLDERING

- Substitution of silver with other metals such as tin is possible, although the physical and chemical performance in these applications of tin is reduced (BGR, 2016).

BATTERIES

- Nickel is a significant substitute of silver in batteries (SCRREEN2 Validation workshop, 2022).

PHOTOGRAPHY

- Several substitution options exist to replace silver in traditional photographic applications. For example, film with reduced silver content, silver-frees black-and-white film, and xerography (USGS 2020).

MEDICINE

- Surgical pins and plates can be made with stainless steel, tantalum, and titanium, instead of silver (however this would entail using other critical materials in some instances).

GLASS

- Aluminum and rhodium can replace silver that is used in mirrors and other reflecting surfaces.

AUTOMOTIVE

- Silver itself can replace more expensive metals in catalytic converters (for off-road vehicles) (USGS, 2022).

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SUPPLY

EU SUPPLY CHAIN

Silver is assessed at the extraction stage in the form of silver ores and concentrates (EU trade code CN 26161000: Eurostat, 2022). The common trade products in the processing/refining stage include colloidal silver, silver nitrate, silver oxides and hydroxides, and metal silver (incl. plated with gold/platinum) in unwrought, powder, or semi-manufactured form.

According to the Silver Institute, in 2021 the global supply of silver, including primary and secondary sources, reached 31,017 t, which is a 5% increase over 2020, whereas the demand was slightly higher with 32,622 t (a 19% increase over 2020) (Metal Focus Team 2022). The strongest increase of demand were in the fields of physical investment, jewelry, silverware, and photovoltaics.

In 2020, domestic silver mining within the EU produced 1,961 t Ag (Eurostat, 2022). This amount mostly feed into European supply chains, reducing the import reliance. The net import into the EU (= 29,188 t import – 5,881 t export) was 23,307 t of silver, with main suppliers outside European being Mexico, Bolivia, Argentina and Peru (Figure 1). Main export partner for silver ores and concentrates is China with ~90% (Figure 17).

According to the OECD, worldwide applicable trade restrictions for silver are imposed by Indonesia (since 2014 export prohibition), Bolivia (since 2014 a 0.05% fiscal tax on the export gross value), and Russian Federation (since 2010 a domestic market obligation). China eliminated the export tax of 10% for silver ores and concentrates in 2019 (OECD, 2022).

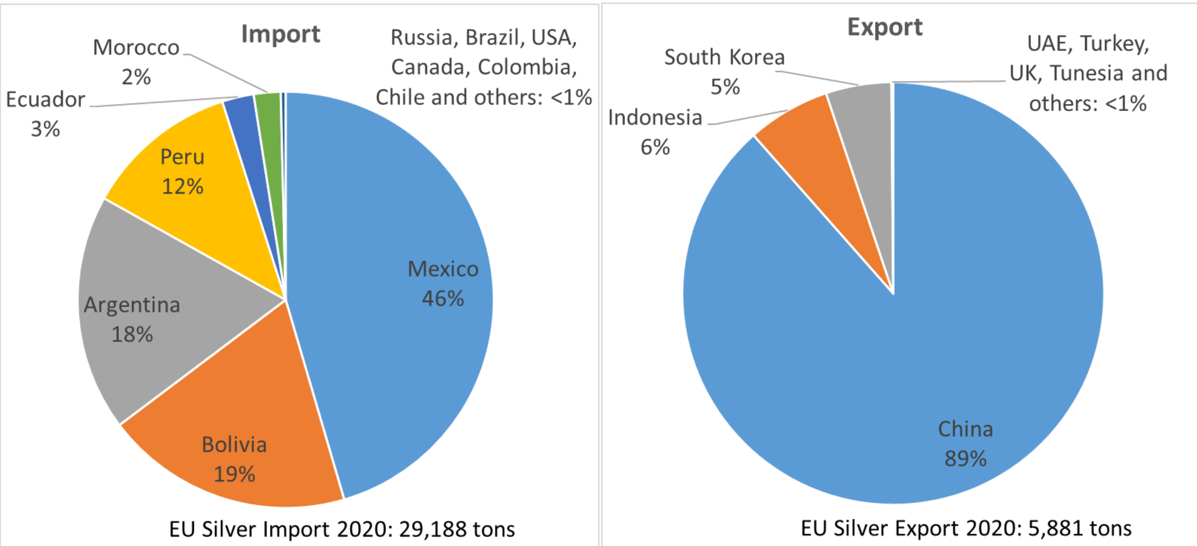

Figure 17: EU partners for silver ores and concentrate import and export in 2020 (Eurostat, 2022).

The post-consumer functional recycling of silver scrap and silver jewellery and silverware is well established, contributing to silver supply from secondary sources. The End-of-life Recycling Input rates of silver in 2020 are 18.65% (global) and 4.23% (EU), with both rates showing a steady increase over the past years (Eurostat, 2022). The Silver institute shows recycling figures for the EU for 2021 (total of 1007 t), with Germany (300 t),

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Italy (141 t), and France (104 t) being the main recycling countries (Metal Focus Team, 2022). High silver prices were an important catalyst for the rising of global and European silver recycling. Most of the increased volumes came from jewelery and silverware, especially in India. Scrap generated from industrial end-uses, the biggest source of global silver recycling, also rose (Eurostat, 2022).

SUPPLY FROM PRIMARY MATERIALS

GEOLOGY, RESOURCES AND RESERVES

GEOLOGICAL OCCURRENCE

Silver can be extracted from a variety of deposit types, as it concentrates in numerous geological environments. It usually occurs in four forms: as a native element, as a primary constituent in silver minerals, as a natural alloy with other metals, and as a trace to minor constituent in the ore of other metals. Native silver is infrequently found in nature. It is usually associated with quartz, gold, sulphides or arsenides of other metals, and other silver minerals. Most of native silver is associated with hydrothermal deposits, as veins and cavity fillings. More than 39 silver-bearing minerals have been identified: most prominent are sulphides, such as acanthite (Ag_2S), proustite (Ag_3AsS_3) and pyragyrite (Ag_3SbS_3), but there are also silver-bearing tellurides, halides, sulphates, sulphonates, silicates, borates, chlorates, iodates, bromates, carbonates, nitrates, oxides, and hydroxides. As a natural silver-alloy, silver is for the most part combined with gold. The term 'electrum' is used for minerals in which the silver/gold ratio is at least 20%. Silver can also be alloyed with mercury (i.e. 'silver amalgam').

In most cases the economic viability of deposits that contain silver depends upon the presence of other valuable minerals. Therefore, 'silver deposits' rarely exist as such. the major share of Ag is obtained as a by-product from gold, copper, lead or zinc mining. In these ore types, silver either occurs as a substituted element in the ore mineral's lattice, or as an inclusion of native silver or silver-minerals. These ore minerals are typically the common base metal sulfides galena (PbS), sphalerite (ZnS), chalcopyrite ($CuFeS_2$).

GLOBAL RESOURCES AND RESERVES[1]

The world's proven and probable silver reserves were estimated to be approximately 530,000 t (Table 7). Peru, Poland and Australia are hosts of the largest silver reserves (USGS, 2022).

According to The Silver Institute, global reserves at primary silver mines and projects totaled 106,136 t in 2021 (Metal Focus Team, 2022). The 4.2% (4.597 t), year-on-year decline was driven by mining depletion alongside reserve revaluation. Total identified resources excluding reserves are 236,584 t, an increase of 1.0% year-on-year increase resulting from near-mine expansions and newly discovered resources (Metal Focus Team, 2022).

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Table 7. Global silver reserves (USGS, 2022). (NA data not available; #Joint Ore Reserves Committee-compliant or equivalent reserves were 25.000 t.)

Country	Reserves Ag [t]	%
Peru	120,000	11.3
Australia#	90,000	8.5
Poland	67,000	6.3
Russia	45,000	4.2
China	41,000	3.9
Mexico	37,000	3.5
United States	26,000	2.5
Chile	26,000	2.5
Bolivia	22,000	2.1
Argentina	NA	NA
Kazakhstan	NA	NA
Other countries	57,000	5.4
World total (rounded)	530,000	50.0

EU RESOURCES AND RESERVES[2]

Resource information for Spain, Portugal, Poland, Slovakia, Czechia are available at Minerals4EU (2019) (Table 8) but cannot be summed as they are partial and they do not use the same reporting code.

Table 8: European silver reserves data compiled in the European Minerals Yearbook of Minerals4EU (Minerals4EU, 2019, data from 11/2014)

Country	Classification	Reserves [t]	ore grade [g/t Ag]	Reporting code
Sweden	Proven	517,100,000	5.2	FRB-standard
	Proven	12,300,000	69.0	NI 43-101
Finland	Proven	7,400,000	14.0	NI 43-101
	Proven	1,800,000	98.0	JORC
Portugal	Proven	16,521,000	62.4	NI 43-101
Poland	Total	70,740	Ag content	Nat. Rep. Code
Slovakia	Z1	7,335,000	12.0	None
Ukraine	(RUS)C1	4,136,500	-	Russian class.
	(RUS)C1	158	Ag content	Russian class.
Kosovo	(RUS)A	13,250,000	78.8	Nat. Rep. Code
Greece	Proven	2,200	-	CIM
Turkey	Proven	4,490,000	27.0	NI 43-101
	Proven	20,510,000	1.3	JORC

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GLOBAL AND EU ORE PRODUCTION

Mexico is the world's largest silver ore producer, contributing about 24% of the total world supply. This counry is by far the largest producer of silver ore, while most other countries produce silver as a by-product from mines targeting other metals. In 2021, 72% of mined silver production came from lead-zinc, copper, and gold mines (Table 9).

Other important suppliers of silver (ores and concentrates) are Peru (14%), China (13%), all three account for more than 50% (Figures 3). The EU mine production of silver is concentrated in Poland and Sweden, their base metal mines account for 63% and 22% of EU production (Figure 4, 2016-2020 average). There are several other silver producing countries within the EU: Bulgaria, Spain, Portugal, Greece, Romania, Finland, Ireland, Germany, Slovakia, and Cyprus.

Table 9. Silver mine production by source metal in 2021. Source: Metals Focus 2022, recalculated from million ounces.

World region	Lead/Zinc	primary Silver	Copper	Gold	Other
North America, (incl. Mexico)	1017	4005	409	1938	12
Central & South America	2170	1407	2396	1147	0
Europe	440	47	1519	40	0
Africa	112	202	105	112	0
CIS	341	614	729	291	68
Asia	3168	335	1125	282	47
Oceania	589	518	171	146	0
Total	**7837**	**7127**	**6454**	**3956**	**130**

In 2021, the global mined silver production increased by 5.3% over 2020, reaching 25.587t. The increase in silver production was accompanied by an increased lead (+3.8%), zinc (+4.5%), gold (+2.5%), and copper (+2.2%) production (Metals Focus Team, 2022). This was the biggest annual growth in mined silver supply since 2013 and was primarily driven by the recovery in output following COVID-19 related disruption in 2020 (Metals Focus Team, 2022). However, silver production was lower than the forecast in the 2021 World Silver Survey, as several large mines struggled to meet production guidance and operations were unexpectedly suspended at Buenaventura's Uchucchacua mine in Peru.

Silver production in Europe increased by 5.7% over 2020 to 2,050t as higher grades at KGHM's operations in Poland improved silver production in concentrate by 7.0% to 1,303t. In Sweden, by-product output from base metal operations also increased, up 3.8% to 432t (Metals Focus Team, 2021).

Across Europe, there are some exploration activities underway in the EU member states Ireland, Spain, Portugal, Romania, Slovakia, Hungary, Poland, and Sweden, as well as in The UK, Kosovo, and Switzerland (Minerals4EU, 2019).

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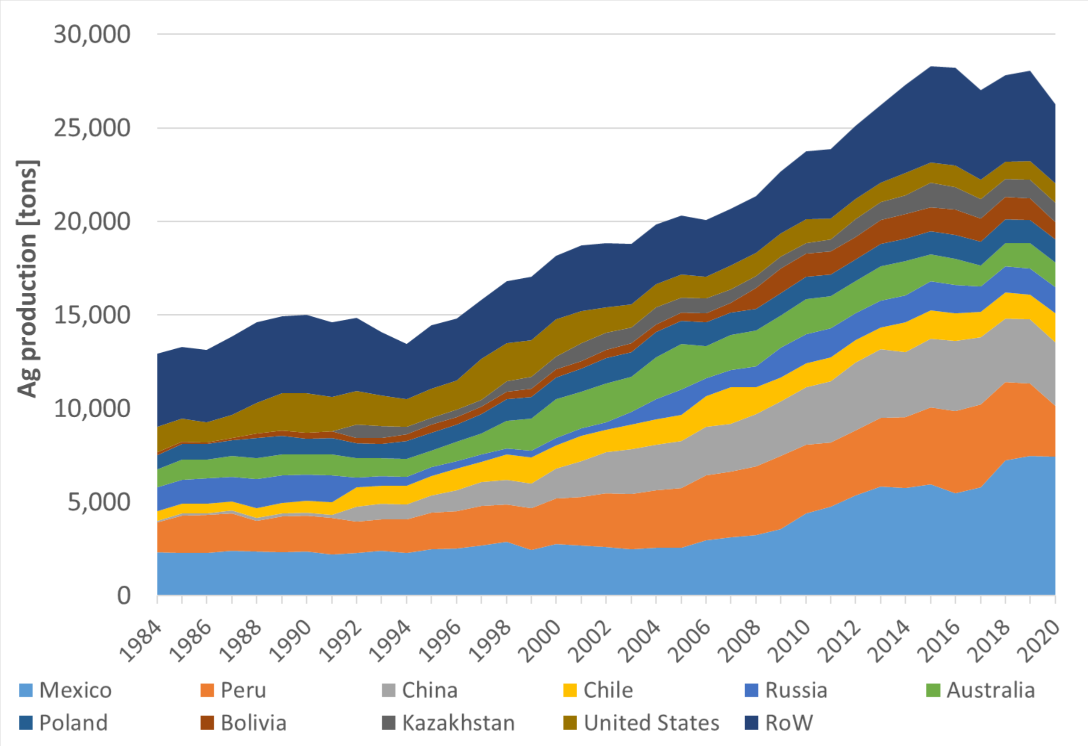

Figure 18: Global silver production from 1984 to 2020 (WMD, 2022).

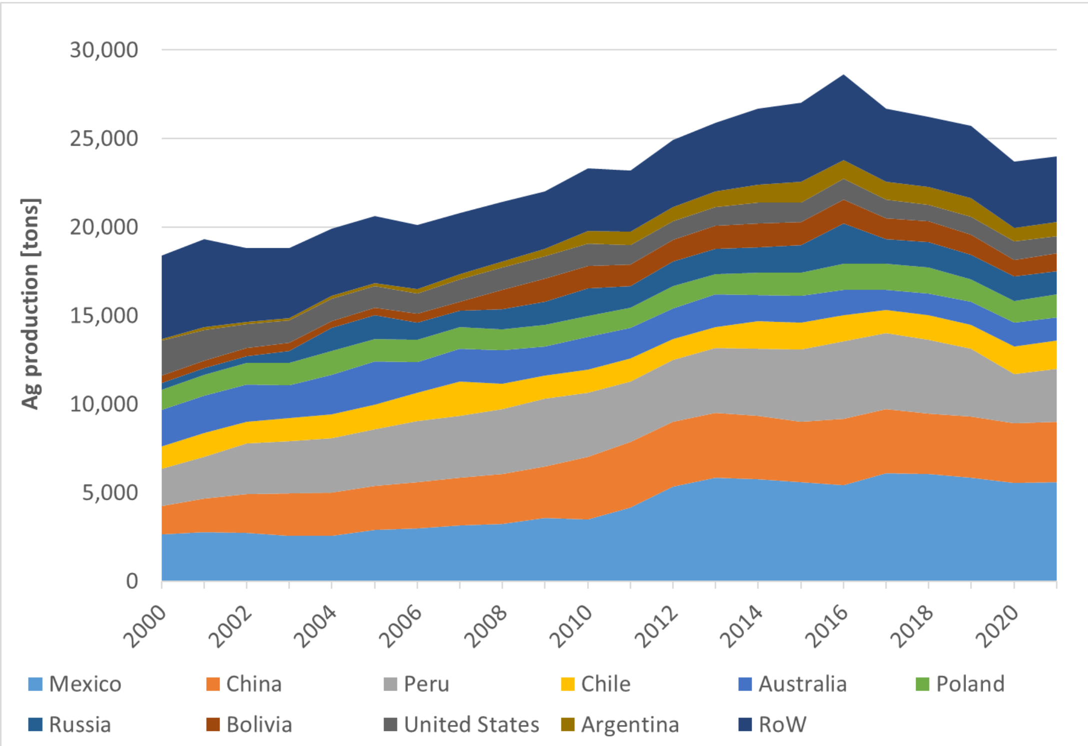

Figure 19: Global silver production from 2000 to 2021 (USGS Mineral Yearbooks, 2000 - 2022).

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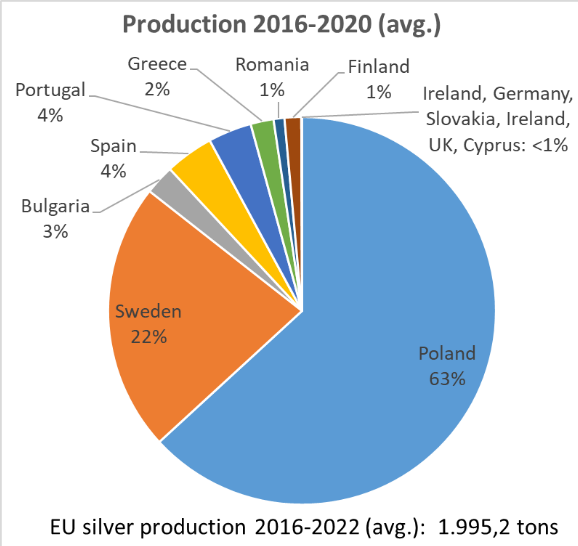

Figure 20: Silver ores and concentrates production within EU member states, average for the years 2016-2020 (WMD, 2022).

WORLD AND EU PRIMARY SILVER REFINERY PRODUCTION

The annual EU sourcing for refined silver metal accounts for 5,261 t, between 2012 and 2016. The 68% of this sourcing comes from domestic production within the EU and the remaining 32% is imported from other countries. Germany is the biggest domestic producer with 32% ot EU production. Italy produced 24%, France 13% and Belgium 13% of silver metal respectively. -> from 2020, needs recent numbers

Jewellery (21%) and photovoltaics (15%) represent the main industries using refined silver within the EU (Eurostat, 2022). Others industries include silverware, catalysts (in the automotive industry and others), brazing and soldering, batteries, electronic parts, glass, bearings, medicine, and photography. The largest contributor to refining is the German industry, contributing around 10% of the world's industrial silver, as in 2020.

The industrial fabrication of silver products in the EU has risen steadily since 1990, but has shown a slight decline in recent years. In 2021, silver jewellery fabrication in Europe rebounded by 23% to 943 t achieving an 11-year high. This recovery was largely based on a jump in exports plus restocking by regional retailers and a recovery in local consumption (Metals Focus Team, 2022). The photovoltaic market expands globally, and there were 20 countries that achieved 1GW last year (Metal Focus Team 2022). Those record high photovoltaic installations helped silver to reach 3,536 t in 2021.

OUTLOOK FOR SUPPLY AND DEMAND

The global demand in jewellery is forecast to grow by 11% in 2022, and in silverware by 23%, with India largely behind these gains (Metals Focus Team, 2022). Industrial silver demand is expected to grow with the increasing efforts towards the renewable energy production, electric vehicle (EV) manufacturing, and digitalization, globally. Especially, the photovoltaic market continues to expand and to spread geographically. The use of silver in EV technology (cameras, sensors, LiDAR, GPS, in-house chargers, and curb-side charging stations) is

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resulting in a demand for silver-coated or silver-alloy wires that may rise at a faster pace than mere vehicle production numbers (Metals Focus Team, 2022).

The Silver Institute forecasts for 2022 that by-product silver production increases most significantly from gold mines, This will be driven by the commissioning of the silver-rich La Coipa gold project in Chile but also from higher output from several existing operations alongside (Metals Focus Team, 2022). Silver production rises modestly from copper mines and remain almost flat from lead-zinc operations.

Global recycling is forecast to rise by over 4% in 2022 to 5,616 t, representing a 10-year high (Metals Focus Team, 2022). Recycling is led by gains in industrial scrap supply.

SUPPLY FROM SECONDARY MATERIALS/RECYCLING

The end-of-life recycling input rate for silver globally is estimated to be 19% in 2020. It must be said that several other percentages of the End-of-life recycling input rate (EoL-RIR) are reported, ranging between 20% (GFMS, 2015; 2019) and 80% (UNEP, 2011) (SCRREEN workshops 2019). At European level, the EoL-RIR is 4,23%, being the highest rate registered due to the high silver price.

Most of the increased volumes, both globally and at European level, came from jewellery and silverware. Scrap generated from industrial end-uses, the biggest source of global silver recycling, also rose.

Recycling rose for a second year in a row, up 7% in 2021 to an eight-year high of 5,382t. (GFMS,2022).

Recycling is set to increase for a third straight year in 2022 with a 4% gain forecast. This will again be led by the industrial sector where the drivers from last year (higher ethylene oxide, EO, change-outs and the normalization of collection and processing) will continue to aid volumes in 2022, albeit to a lesser extent than last year. Smaller contributions will also stem from the recovery of silver from old jewellery and silverware (GFMS, 2022).

Jewellery, silverware and coins have very high recycling rates, typically greater than 90% due to the ease of collecting and recycling of these applications. Once these applications are excluded from the calculation; the EoL-RR for silver falls in the range 30%-50%. High-grade jewellery scrap is usually re-alloyed on-site rather than being refined. Jewellery sweeps, the fine dust generated in the polishing and grinding of precious metals, are usually smelted to form an impure silver, which is electro-refined. Because of the much lower value of silver scrap, recycling techniques applicable to gold (e.g., cyanidation of low-grade scrap) are uneconomic for silver. Low-grade silver scrap is instead returned to a smelter for processing.

- However, the EoL-RR varies considerably by application (UNEP, 2011):
- Vehicles (electric and electronic parts): 0%-5%
- Electronics: 10%-15%
- Industrial Applications: 40%-60%
- Others: 40%-60%

For applications where silver use is less dissipative, such as in electric and electronic parts in vehicles and electronics, losses occur in collection, shredding and metallurgical recovery operations. For electronics

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specifically, recovery rates at state-of-the-art metallurgical plants can be close to 100% of the silver contained, if the printed circuit boards are appropriately collected and pre-treated. In comparison to electronics, industrial applications such as photography and catalysts have a relatively low recycling rate.

PROCESSING OF SILVER ORE

Specific extractive metallurgy processes are applied to a silver-bearing mineral concentrate depending on whether the major metal is copper, zinc or lead. It should be noted here that heap leaching is quite popular around the world (though not taking place in Europe) as a lower capital cost extraction method not only for gold but for silver containing concentrates as well (Manning and Kappes, 2016).

The smelting and converting of copper sulfide concentrates result in a “blister” copper that contains 97% to 99% of the silver present in the original concentrate. Upon electrolytic refining of the copper, insoluble impurities, called slimes, gradually accumulate at the bottom of the refining tank (McQuinston, 1985). These contain the silver originally present in the concentrate but at a much higher concentration.

The slimes are then smelted in a small furnace to oxidize virtually all metals present except silver, gold, and platinum-group metals. The metal recovered, called doré, is cast to form anodes and electrolyzed in a solution of silver-copper nitrate. Two different electro-refining techniques are employed, the Moebius and Thum Balbach systems (Mooiman and Simpson, 2016). The chief difference between them is that the electrodes are disposed vertically in the Moebius system and horizontally in the Thum Balbach system. The silver obtained by electrolysis usually has a purity of 99.99% silver.

Lead concentrates containing silver are first roasted and then smelted to produce a lead bullion from which impurities such as antimony, arsenic, tin, and silver must be removed. Silver is removed by the Parkes process, which consists of adding zinc to the molten lead bullion (Figure 5). Zinc reacts rapidly and completely with gold and silver, forming very insoluble compounds that float to the top of the bullion (911Metallurgist.com). These are skimmed off and their zinc content recovered by vacuum retorting. The remaining lead-gold-silver residue is treated by cupellation, a process in which the residue is heated to a high temperature (about 800°C) under strongly oxidizing conditions. The noble silver and gold remain in the elemental form, while the lead oxidizes and is removed. The gold and silver alloy thus produced is refined by the Moebius or Thum Balbach process (Mooiman and Simpson, 2016). The residue from silver refining is treated by affination or parting to concentrate the gold content, which is refined by the Wohlwill process.

Silver is still also produced by lead sulfides through the historical pyrometallurgical process of roasting, reduction and cupellation. Galena is converted to Ag-containing PbO thorough oxidative roasting. Lead oxide is then reduced with carbon agent. Ag is separated by the Ag-Pb alloy via cupellation (oxidative smelting between 960 and 1000 ^{o}C). Lead oxidizes to lead monoxide, known as litharge, while metallic Ag received superficially.

Zinc concentrates are roasted and then leached with sulfuric acid to dissolve their zinc content, leaving a residue that contains lead, silver, and gold—along with 5% to 10% of the zinc content of the concentrates. This is processed by slag fuming, a process whereby the residue is melted to form a slag through which powdered coal or coke is blown along with air. The zinc is reduced to the metallic form and is vaporized from the slag, while the lead is converted to the metallic form and dissolves the silver and gold. This lead bullion is periodically collected and sent to lead refining, as described above (911Metallurgist, 2019). Commercial-grade fine silver is at least 99.9% pure, while silver products with purity > 99.999% are available.

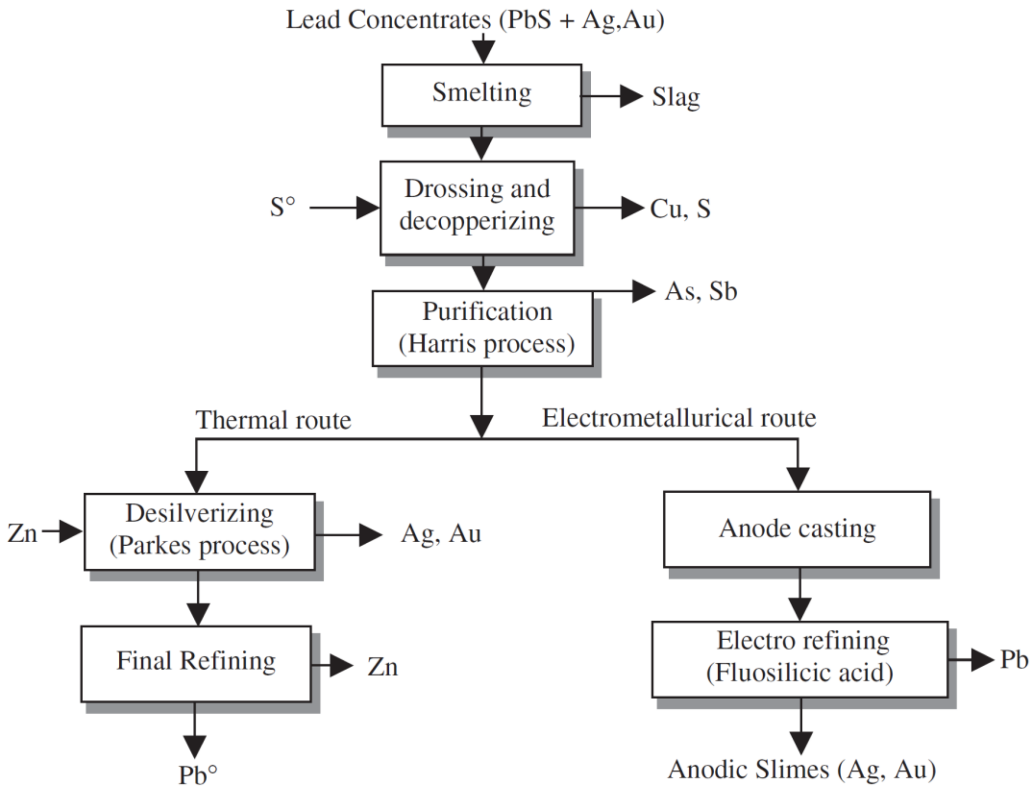

Figure 21: Parkes method for silver recovery through the processing of Au-Ag containing lead sulfide ore (Ferron, 2016).

OTHER CONSIDERATIONS

HEALTH AND SAFETY ISSUES RELATED TO SILVER OR SPECIFIC/RELEVANT COMPOUNDS AT ANY STAGE OF THE LIFE CYCLE

Silver is a non-combustible substance, poorly flammable and practically insoluble in water. The substance is hazardous to the aquatic environment. According to (GESTIS 2022), the limit value (eight hours) of silver in air is 0.1 mg/m^3 in the European Union[5], which is higher than in the US where the limit value is 0.01 (GESTIS 2022).

Silver is listed under Annex XVII to the REACH (REACH 2022).

The reference dose for oral exposure – with reference to the Dermal system – is 5x10^{-3} mg/kg per day. (IRIS 1991)

[5] Indicative Occupation Exposure Limit Value (IOELV)

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An assessment of four silver-containing activated carbon water filters showed that the filtered water poses unacceptable risks to human health. (ECHA Europa EU 2021)

WHO, US EPA and the Australian EPA have established drinking water limits of 100 ppb (Fisher et al. 2015). Because of their antimicrobial properties, the use of silver nanoparticles (AgNPs) is increasing fast in industry, food, and medicine. However, controversies remain with respect to their toxic effects and their mechanisms […] Silver nanoparticles can produce free radicals and cause oxidative stress in cells; this mediates toxicity by triggering inflammatory reactions and death by necrosis or apoptosis (Gaillet et al. 2015).

The estimated acute lethal dose of silver nitrate is at least 10 g […] The only known clinical picture of chronic silver intoxication is that for argyria, a condition where silver is deposited on skin and hair and in various organs, and can be especially observed in silver mines workers (WHO 2020).

ENVIRONMENTAL ISSUES

In general, silver is one of the most toxic metals to aquatic life in laboratory experiments. Silver nitrate and silver iodide are particularly toxic, whereas silver chloride is 300 times less acutely toxic (Australian Government, 2000).

Companies registering silver under REACH claimed that the ionic form of silver could be considered as the worst-case scenario when assessing risks for the environment. Authorities, on the other hand, had evidence that in some cases silver nanoforms were more harmful to the environment than the ionic forms (EUON 2022). The most toxic silver species, the silver ion, is essentially the non-complexed quantity of silver passed through a 0.1 µm filter. These silver ions are especially toxic to fish because Ag^+ disrupts the gas exchanges and acid-base regulatory functions (Fisher et al. 2015)

Small-scale miners (including silver mining) use large quantities of mercury, resulting in severe health and environmental damages (Melhus et al. n.a.).

NORMATIVE REQUIREMENTS RELATED TO MINING OR SILVER PRODUCTION, USE AND PROCESSING OF THE MATERIAL

Silver is listed as a biohazardous waste, which means it must be disposed through silver reclamation services. (BWS 2022) Silver waste can be generated during different processes (eg. photo processing). Business guides provide guidance on how to correctly dispose it. (EPA 2022 – see the link https://www.epa.gov/hwgenerators/managing-your-hazardous-waste-guide-small-businesses)

SOCIO-ECONOMIC AND ETHICAL ISSUES

ECONOMIC IMPORTANCE OF SILVER FOR EXPORTING COUNTRIES

Table 10 lists the countries for which the economic value of exports of silver represents more than 0.1 % in the total value of their exports.

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Table 10: Economic share of silver exports

Country	Export value (USD)	Share in total exports (%)
Bolivia	7032764187	6.85 %
Mongolia	7576310834	1.64 %
Peru	3,8757E+10	1.45 %
South Africa	8,5227E+10	1.05 %

Source: COMTRADE (2022), based on data for 2020

For Bolivia (6.85 %), Mongolia (1.64 %), Peru (1.45 %) and South Africa (1.05 %) the value of silver ore exports represent more than 0.1 % of the total value of their exports.

The silver market is one-tenth f the size of gold's in London's wholesale dealing (London Bullion Market Association 2022 – link to precious metals price https://www.lbma.org.uk/prices-and-data/precious-metal-prices#/). The market for silver is also more volatile (Reddy 2022).

SOCIAL AND ETHICAL ASPECTS

The exploitation of silver mines carried out informally by individuals (artisanal mining) could generate more contamination, as chemicals are used (sulfuric acid, cyanide, sodium etc.), which are highly polluting for the water and the environment. At the same time, even though legal persons involved in mining might follow stricter technical norms, they can still produce negative effects on the environment and on the society (Méndez et al. 2015)

Silver mining, and mining in general, can be related to several social and ethical issues, including but not limited to labour exploitation, lack of safety in the working environment, child labour, land conflict etc. (Okyere 2022). There is the need to undertake a sustainable development approach, where the three dimensions of environment, social component and economic component are considered together. (Méndez et al. 2015).

RESEARCH AND DEVELOPMENT TRENDS

RESEARCH AND DEVELOPMENT TRENDS FOR LOW-CARBON AND GREEN TECHNOLOGIES

- Ag-doped cathode application in fuel cells

Silver (Ag) can contribute to tackling climate change and reducing CO_2 emissions. Several ongoing studies analyse its use in fuel cells as a doping[6] agent in cathodes. Sazinas R. et al. (2019) used synthesised Ag-doped perovskite as a cathode ($La_{1-x-y}Sr_xAg_yMnO_{3-\delta}$ (LSAM)) to increase the efficiency of the oxygen reduction reaction, which is one of the core steps of the electricity generation in fuel cells. The authors conducted experiments to evaluate the electrochemical performance of the Ag-doped cathode and compare it with two undoped systems made of $La_xSr_yMnO_{3-\delta}$ (LSM). In these undoped LSM systems, two materials were used as

[6] Doping is a strategy to enhance the electrochemical energy storage performance of layered cathode materials (H. Hohyun Sun, et al. 2021).

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electrolysers, 8 % yttria-stabilized zirconia (YSZ) and 10 % gadolinia-doped ceria (CGD). The three cathodes were inserted in symmetric fuel cells and analysed at 600 °C and 500 °C. At 600 °C YSZ and CGD fuel cells showed an area-specific electric resistance of 2.2 and 1.3 Ω cm^2, respectively. On the other side, the Ag-doped specimen performed with a lower resistance, 0.21 Ω cm^2, when the system ran at 500 °C. According to the study's conclusions, this low resistance indicates the excellent performance of the LSAM cathode, thus meaning that it "may be an efficient cathode material for oxygen reduction reactions".

- Ag potential application in microbial fuel cells

Silver has been gaining increasing attention for its potential application in microbial fuel cells, given its long-term stability, high conductivity, and good catalytic activity. Additionally, Ag has antibacterial properties and thus can poison microbial cells, reducing problems caused by biofouling[7] (Noori, Md. T. et al., 2016). Farahmand Habibi, M. et al. (2022) ran experiments with various microbial fuel cell cathodes and compared their electrochemical performances. For this scope, silver/silver tungstate nanorods (Ag/Ag_2WO_4) were used to decorate[8] carbon support materials, namely graphene, carbon Vulcan and functionalised multi-walled carbon nanotubes (f-MWCNTs). Platinum-carbon (Pt/C) cathode was taken as a reference for comparison. The best performance was reached by Ag/Ag_2WO_4@f-MWCNTs, with a current density of 6.43 A/m^2, which is higher than the reference material's 5.43 A/m^2. The power density of Ag/Ag_2WO_4@f-MWCNTs was also higher than Pt/C (0.965 W/m^2 and 0.893 W/m^2, respectively). The study demonstrated that MWCNT enrichment with Ag/Ag_2WO_4 not only increases its electrical conductivity and surface area but also might enrich oxygen diffusion and facilitate oxygen reduction reactions in microbial fuel cells.

- Polypropylene (PP) films employment to avoid the corrosion of the silver grid in PV modules

One of the leading causes of photovoltaic (PV) module degradation and loss of performance is the corrosion of the silver grid used as conductive material between silicon layers due to humidity penetrating the module (Kim J. et al., 2021). Oreski, G. et al. (2021) substituted the polyethene-terephthalate (PET) back-sheet of PV modules with co-extruded polypropylene (PP) films, raising its reflectance and leading to an increase in power output between 1.5 and 2.5 %. Interestingly, the change in the material also prevented humidity from entering the PV module, which corroded the silver grid and reduced the system's efficiency. Thus, the research demonstrated that the change in the back-sheet material improves the module's performance also in the long term, decreases silver grid corrosion, and finally increases the PV module's service life.

- Ag nanowire anode application in optoelectronic techniques

Ricciardulli A. et al. (2018) developed a flexible and transparent anode made of Ag nanowires and exfoliated graphene for optoelectronic applications such as organic solar cells and polymer light-emitting diodes. This system has the potential to substitute indium tin oxide in electrodes. This transparent conductive electrode is widely used in optoelectronics, given its high optical transparency and electrical conductivity. However, it has the downside of high production costs, low supply, and poor chemical and mechanical stability. Pure Ag nanowires show high levels of transparency and low electrical resistance. Still, it also entails some drawbacks, such as percolation of charges through junctions, and high surface roughness, which is incompatible with LED production needs. Thus, the study results show that Ag nanowires and exfoliated graphene synergy lead to a

[7] Biofouling or biological fouling is the adhesion of microorganisms to surfaces and the development of biofilms (Patel et. al, 2021).
[8] Decoration is the modification of carbon nanotubes surface with metal nanoparticles to enhance their electrical properties (Gurylev, V. et al., 2019).

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transparent conducting material characterised by a smooth surface and excellent mechanical, chemical and electrical properties that can be adapted to many optoelectronic applications.

OTHER RESEARCH AND DEVELOPMENT TRENDS

- Silver Isotopes and the Rise of Money (H2020, 2017 – 2024)[9]

Silver was the primary metal of economic exchange and military finances in ancient Mediterranean and Near-Eastern societies. Silver isotopes will help quantify monetization of these societies by identifying Ag mineral sources, monetary sinks, and its major transfer routes. The project will address major questions: (i) understand the sources of unmined silver as a precursor to coinage; (ii) use Ag isotope fingerprinting of the earliest coinages of Athens to identify the contributions of Greek mines to the development of the world's first democracy; (iii) map the Greek and Persian mines which sourced the treasure captured by Alexander the Great, and investigate the spread of its silver; (iv) study the causes of the monetary reform of the Roman Republic in 211 BC; and (v) model the silver cycle from mines to coinage and artefacts in its economic context.

- Adsorptive removal of thiophene by using water-based silver nanofluid (2022)[10]

In this work, a simple, eco-friendly, and energy-efficient protocol was used for the removal of thiophene as a model for the sulfur compounds present in gasoline. The water-based silver nanofluid was prepared via the chemical reduction method, using tannic acid as both a reducing and stabilizing agent. The prepared silver nanoparticles (AgNPs) were characterized using X-ray diffraction (XRD), dynamic light scattering (DLS), ultraviolet–visible spectroscopy, and transmission electron microscope (TEM). For studying the adsorption efficiency of the silver nanoparticles, several parameters were evaluated, such as the contact time, the size and stability of the nanoparticles, the concentrations of AgNPs, and the thiophene. The silver nanoparticle, of size 8.3 ± 2 nm, showed the highest adsorption efficiency (i.e., 88.4 %) from thiophene solution (500 ppm) (190.5 ppm S). The adsorption process underwent a pseudo-second-order. Furthermore, the adsorption mechanism was studied. The results could be attributed to the partially replacing of the capping agent, i.e., tannic acid, with thiophene, which is considered a hydrophobic agent, during the agitation process. Accordingly, the silver nanoparticle, contaminated with sulfur compounds, spontaneously migrated to the oil/water interface. AgNPs capped with thiophene were characterized using field emission-scanning electron microscope (FE-SEM), transmission electron microscope (HR-TEM), EDX-mapping, and dispersive Raman microscope. This approach provides a new way to remove thiophene by using the aqueous fluid of silver nanoparticles.

- Green in-situ synthesis of silver coated textiles for wide hygiene and healthcare applications (2022)[11]

In this study, antibacterial and biocompatible silver-based (Ag0) coatings on cotton fabric were obtained by using atmospheric pressure plasma mediated in situ silver reduction, an effective, facile, and environment-friendly technique. The formation of the thin (nanometers in thickness) Ag0 coating on the fabric fibers was

[9] https://cordis.europa.eu/project/id/741454
[10] https://www.sciencedirect.com/science/article/abs/pii/S0016236122034081
[11] https://www.sciencedirect.com/science/article/abs/pii/S0927775722022610

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characterized by scanning electron microscopy (SEM) and backscattered electron (BSE) analysis. In particular, the antibacterial activity demonstrated by the silver-fabrics (Ag0-fabrics) against gram-negative (Escherichia coli) and gram-positive (Staphylococcus aureus) bacteria was about 105 times more potent than silver ion or silver nanoparticle fabricated fabrics. The Ag0-fabrics also demonstrated good killing activity to preformed biofilms. Moreover, because of the greatly reduced silver loading, Ag0-fabrics did not pose significant cytotoxicity to human tissue cells exhibiting good biocompatibility. Given the economic and environment-friendly nature of the Ag0-fabrics technology wide applications can be derived in health, hygiene, and medical fields.

- Investigation on thermal conductivity of silver-based porous materials by finite difference method (2022)[12]

Porous materials are widely used in the electronics industry and biomedical fields, where sintered silver, as an emerging representative of porous media, is a promising chip-connection material for adoption in third-generation power electronics. One of the important parameters to characterize the heat conduction capacity of porous sintered silver is the thermal conductivity. In this paper, a numerical model for calculating the equivalent thermal conductivity of porous silver is proposed, based on a voxelized mesh, using finite difference method (FDM) instead of the commonly used finite element method (FEM). Comparisons between the two methods are carried out for the classical unit cells such as simple cubic, body-centered cubic, and face-centered cubic, as well as the silver-based stochastic model. The developed finite difference algorithm is valid, and consistent results are obtained.

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[12] https://www.sciencedirect.com/science/article/abs/pii/S235249282201738X

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